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Characterising agrometeorological climate risks and uncertainties: Crop production in Uganda

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Uganda is vulnerable to climate change as most of its agriculture is rain-fed; agriculture is also the backbone of the economy, and the livelihoods of many people depend upon it. Variability in rainfall may be reflected in the productivity of agricultural systems and pronounced variability may result in adverse impacts on productivity. It is therefore imperative to generate agronomically relevant seasonal rainfall and temperature characteristics to guide decision-making. In this study, historical data sets of daily rainfall and temperature were analysed to generate seasonal characteristics based on monthly and annual timescales. The results show that variability in rainfall onset dates across Uganda is greater than the variability in withdrawal dates. Consequently, even when rains start late, withdrawal is timely, thus making the growing season shorter. During the March–May rainy season, the number of rainy days during this critical period of crop growth is decreasing, which possibly means that crops grown in this season are prone to climatic risks and therefore in need of appropriate adaptation measures. A time-series analysis of the maximum daily temperature clearly revealed an increase in temperature, with the lower limits of the ranges of daily maximums increasing faster than the upper limits. Finally, this study has generated information on seasonal rainfall characteristics that will be vital in exploiting the possibilities offered by climatic variability and also offers opportunities for adapting to seasonal distribution so as to improve and stabilise crop yields.

Introduction

Uganda is vulnerable to climate change, as most of its agriculture is rainfed[1]; yet agriculture is the backbone of the economy, and the livelihoods of many people depend on it.[2] Any slight variability in rainfall may therefore be reflected in the productivity of agricultural systems and pronounced variability may result in adverse physical, environmental and socio-economic impacts. Common physical impacts may include drought or floods, environmental impacts may include the loss of biodiversity and vegetation cover and socio-economic impacts may include famine and transhumance. Rainfall across the country is currently unreliable and highly variable in terms of its onset, cessation, amount and distribution, leading to either low crop yields or total crop failure.[3] In addition, the use of rudimentary implements, poor crop husbandry practices and a lack of precise information on rainfall onset, duration, amount and cessation make smallholder farming a risky business.

In most instances, farmers start tilling land after the onset of rainfall, and therefore valuable moisture is lost before they finally plant. In reality, potential crop productivity is never attained as a result of a mismatch between the timing of optimum moisture conditions and the crop's peak water requirements. Farming is therefore prone to risks because of the seasonal distribution and variable nature of rainfall in space and time, coupled with its unpredictability. Extreme climatic variability, such as droughts and floods, has severe impacts on agricultural production, often leading to instability in agricultural production systems.[4] The National Adaptation Programs of Action (NAPA)[5] note that poor rains affect pastures and livestock in most pastoral areas of the country, resulting in the migration of thousands of people and their animals in search of water and food. Jennings and Magrath[6] observed that rains excessive in both intensity and duration lead to water-logging that negatively affects crops and pasture. These conditions are also detrimental to the post-harvest handling and storage of crops. It is therefore essential to generate seasonal characteristics in order to use rainfall regimes optimally for maximum production *vis-à-vis* water use efficiency. Furthermore, given the implication of long-term projections for climate change, generating seasonal characteristics will not only be important in guiding strategic and tactical decision-making, but will also define the direction of change along the weather-climate continuum for planning adaptation strategies.

According to the Food and Agriculture Organization,[7] risk exists when there is uncertainty about the future outcomes of ongoing processes or about the occurrence of future events. Adaptation is about reducing and responding to the risks that climate change pose to people's lives and livelihoods. Reducing uncertainty by improving the information base and devising innovative schemes for insuring against climate change hazards are important for successful adaptation, which was the motivation for this study. This risk in agricultural productivity is not confined to Uganda, but exists for other countries in sub-Saharan Africa. Tadross[8] reported that Mozambique's exposure to the risk of natural disasters would increase significantly over the coming 20 years and beyond as a result of climate change. It is therefore vital that decision-makers are made aware of this risk and act now to incorporate climate change risks into infrastructural planning and investments, as well as to establish national response plans to climate change.

Uganda climatic patterns

According to Phillips and McIntyre[9], the dominant rainfall pattern over East Africa is related to the movement of the Intertropical Convergence Zone. That is, rain falls approximately 1 month after the sun's path coincides with the plane of the equator. With the sun passing overhead biannually, the result is a bimodal rainfall pattern, with the first season occurring from March to May, whilst the second season occurs from October to December. Several studies[10,11] have shown that in both seasons the rain generally falls with the north-easterly winds originating from the Indian Ocean. Further north, the second season tends to peak earlier in August, particularly in Uganda, with the moisture coming from the Congo basin.[9] Therefore the period between the end of the first season and the beginning of the second season is short, making it sufficiently close together to constitute a single rainy season, hence the unimodal rainfall regime.

Uganda experiences moderate temperatures throughout the year. The mean daily temperature is 28 °C. The highest temperatures (over 30 °C) are experienced in the north and north-eastern parts of the country.[5] Sustained warming, particularly over the southern parts of Uganda, has been documented; the fastest warming regions are in the south-west of the country,[5] where, according to Magezi (Magezi A 2010, personal communication, April 01), the rate is of the order 0.053 °C per decade. On the global scale, the 'best estimates' of temperature increases from the Intergovernmental Panel on Climate Change Fourth Assessment Report are in the range 1.8 °C – 4 °C in 2090–2099 relative to 1980–1999, depending on the state of future greenhouse gas emissions, which are used to derive the climate models.[12] It is sufficient to note here that the impacts of temperature increases at even the lower end of this range will be far-reaching.[13]

Seasonal forecasts

Phillips and McIntyre[9] observed that, in Uganda, seasonal climate forecasts were being disseminated in the hope that the information would be useful in regional, or even local, planning and resource management. Efforts to disseminate these seasonal forecasts are based on the assumption that they can be useful at the regional level for food security and water-resource planning, as well as at the individual farm level for planning agronomic activities.[14] Evidence from understanding how climatic uncertainty impacts on agriculture, model-based ex ante analyses and a few well-documented evaluations of actual use and resulting benefits, suggest that seasonal forecasts may have considerable potential to improve agricultural management and rural livelihoods.[15] Forecasts should also enable farmers to select crops that are better adapted to either normal or abnormal rains.[9]

Because of the different rainfall patterns between the south and the north (above latitude 3°N), the cropping systems and the dominant crops also differ.[9] In the north, where the rainfall pattern is unimodal, annual crops such as millet, sorghum, groundnuts and sesame predominate. Whereas, in the south, where the rainfall pattern is bimodal, perennial crops such as banana and coffee predominate.[9] These crops are ordinarily affected by long periods of drought such as those experienced in the north. The cropping systems, including the choice of crop and planting time, are dictated by rainfall distribution and, as mentioned previously, there could be the potential for utilising forecasts of rainfall onset and cessation in crop management.[9]

With this background on the importance of seasonal forecasting, in the current study we aimed to (1) generate interseasonal and intraseasonal rainfall characteristics based on monthly and annual timescales and temperature trends using daily records from 1950 to 2008 and (2) assess the lengths of the growing seasons at different locations and their implications for cropping systems, including the choice of crop and planting time, in order to enhance food security in Uganda.

Methods

Data sets and data properties

The rainfall data used in this study consisted of daily rainfall records for 37 representative stations across 10 agricultural production zones[16] and 14 rainfall zones[17] for the period 1950–2008. The bulk of the daily data was obtained from the Uganda Meteorological Department, with some data also directly obtained from the recording stations in the country. Temperature data were for the period 1950–2008 for Namulonge Station, central Uganda. A time-series trend analysis was constructed using the GenStat Discovery Version 3[18] for daily rainfall and temperature. The trend lines were fitted using linear regression models with the GenStat statistical package.

Homogenisation and estimation of missing data

Development and technological advances can affect the quality of meteorological records either through new equipment or changes in observation routines. As a result, meteorological records cannot be assumed to remain strictly comparable over a long period at all locations. It was therefore necessary to ensure that the records were homogenous. In addition, because of a host of challenges, including poor maintenance of weather stations and inadequate technical capacity, meteorological data in Uganda is not well kept, consistent and regularly analysed,[19] meaning that gaps in the data set needed to be completed. Missing data were estimated using the correlation method and regression techniques. The station most highly correlated with that with missing data was used in the correlation calculations (less than 10% missing record). The quality of the data was examined using residual mass curves as in Ouma[20], Ogallo and Chilambo[21], and Ogallo[22].

Data harmonisation

As a result of the complex climatology of the country and the influence of diverse physical features, it was necessary to identify and harmonise selected stations with homogeneous zones from past studies with similar rainfall characteristics. Basalirwa[17] divided Uganda into 14 rainfall zones using 170 recording stations for the period 1940–1975. After the collapse of the East African Community in 1977, most of the stations in Uganda were abandoned and some closed down because of the restructuring that followed, resulting in a discontinuity in the records at some stations. The current study used only 37 stations with data gaps of less than 10% for the period 1950–2008. It was therefore necessary to first identify how these 37 stations fitted within the homogeneous zones developed from past zonation initiatives by the government[16] and regional bodies[23,24] and other studies such as Basalirwa's[17].

Pentads and cumulative mass curves

Rainfall totals were divided into pentads (or 5-day annual periods) to determine the onset and withdrawal dates of the rainy seasons, such that 01–05 January equated to pentad 1. Pentads have routinely been used to study these characteristics, for example, by Okoola[25]. The advantage of using pentads is that the pentad is a useful unit in dealing with meteorological phenomena in the tropics, especially if the data have to be relevant to applications in agriculture. According to Ogallo[26], a wet pentad is one with 10 mm or more rainfall with at least three rainy days (> 30 mm of rain) to determine the start of the season. A line drawn across the 73 pentads at the 10-mm level indicates the dates of rainfall onset. From the cumulative mass curve, the last pentad of rain corresponds to the first occurrence of a long dry spell when very little rain contributes to the levelling off of the mass curve. Cumulative mass curves were also used in the study to determine the length of the potential crop-growing period. The main advantage of this approach is that it is very simple to use because the duration of the season is calculated as the difference between the pentads of rainfall onset and of withdrawal.

Mass curves are derived from cumulative plots of the rainfall amounts. Cumulative mass curves were plotted for the mean of a group of years in each of the categories: dry years, wet years and average years, generated using principal component analysis methods[27] to generate seasonal characteristics. The result is a visual representation of the cumulated rainfall values as a mass curve. Ogallo[26] observed that during rainy periods much of the rainfall volume is accumulated, and therefore the mass curve reaches its maximum curvature. The onset of the rainy seasons is determined from the curves as the first point of maximum curvature.

Results and discussion

Onset, withdrawal and length of the March–May rainfall season

Cumulative mass curves were generated for all representative locations for the specific homogenous rainfall zones and seasons. An example of the cumulative mass curves that were used to determine the onset and withdrawal of the rains is given in Figure 1. The onset of the seasonal rains was marked as the point of positive maximum curvature on the slopes of the cumulative curve. The pentad of withdrawal corresponds with the point where the mass curve starts levelling off. In that regard, Ogallo[26] and Camberlin and Okoola[28] concluded that the onset generally marks the beginning of a steep gradient on the cumulative curve as a result of the continuous accumulation of a substantial volume of rainfall around the onset date, whilst the withdrawal date is at the end of the slope where the cumulative curve levels off. Cumulative mass curves for all representative locations were used to generate a spatial map (Figure 2) displaying the annual length (days) of the crop-growing period, which ranged from 140 to 340 days.

Table 1 and Figure 3 give the pentads for rainfall onset and cessation in the March–May season at selected stations. Table 1 also gives the length of the planting window and growing season in days. At stations within the bimodal rainfall regime, the pentad range for rainfall onset was 6–20 and the median was 13, whilst for stations in the unimodal rainfall regime the range was 16–23 and the median was 18. This finding indicates that in a few places within the bimodal rainfall regime, rains can start as early as the last week of January, such as Kabale, or as late as the first week of April,

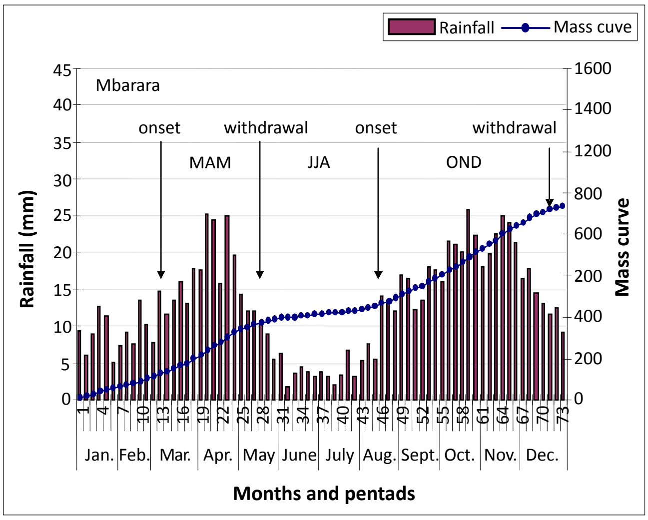


FIGURE 1: Mass curves generated from actual rainfall (>10-mm wet pentad) showing onset and withdrawal of rain for the Mbarara Station in Uganda.

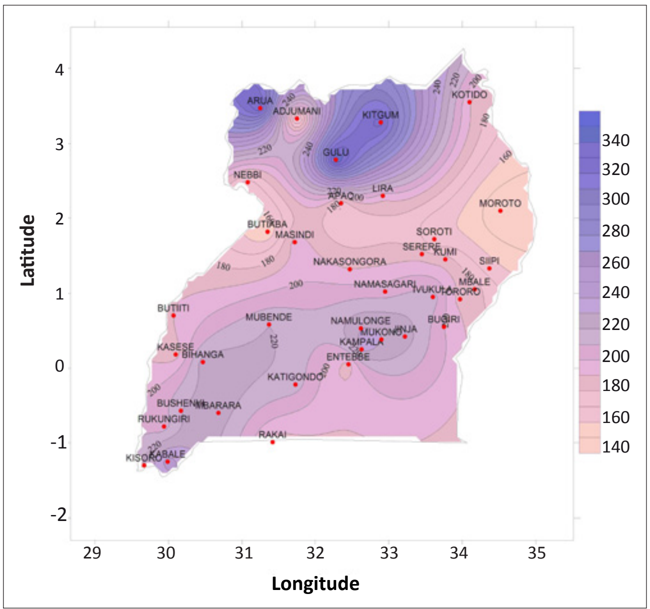


FIGURE 2: Spatial map displaying the annual length (days) of the crop-growing period in Uganda.

as in areas represented by the Mbarara Station. However, for most places within the bimodal rainfall regime, it was typical for the rains to start in the first or second week of March as represented by the median pentad of 13. That notwithstanding, complex topography and large water bodies such as Lake Victoria moderate the rainfall patterns, resulting in a high degree of spatial variability.[26] For most of the bimodal rainfall regime stations, the onset of the March–May season was highly variable from year to year and from one station to the next,[29] as represented by the high standard deviations (Table 1) of about 15 days at Entebbe to 35 days at Mbarara. Such variability creates difficulty in making succinct forecasts for agricultural activities during this season. This variability has been accentuated by climate variability: on many occasions the onset of rains in the March–May season was delayed for as many as 30 days, starting in mid-April instead of mid-March.

The range pentad for rainfall cessation in the bimodal rainfall regime was 27–32, and the median was 30. Rainfall cessation appears to have remained more or less the same, regardless of the onset of rainfall. Consequently, even when rains started late, withdrawal was usually timely, thus making the growing season shorter. Okoola[25] and Camberlin and Okoola[28] associated some of the anomalies in the onset and cessation dates with the large-scale systems that control regional weather such as the El Niño Southern Oscillation (ENSO), cyclones and monsoons.

In the bimodal rainfall regime, the range for the number of growing days was 70–105, the lower limit being experienced by areas represented by Mbarara, Kasese and Rukingiri Stations, all in western Uganda. The upper limit was experienced in areas represented by the Kabale Station, which is located in south-western Uganda at a high altitude. Falling in between the upper and lower limits were areas represented by Katigondo, Entebbe and Namulonge Stations, all of which are in central Uganda. This delineation can be useful in advising on suitable cropping systems, including the choice of crop and planting time.

In areas represented by the unimodal rainfall regime, rains started as early as the third week in March, although it was typical for the rains to start in the first week of April, as represented by the median pentad of 18. At stations experiencing the unimodal rainfall regime, the average onset of rain appears to be rather stable, with standard deviations of 15 days at Nebbi and Yumbe (Table 1). Such stability implies reliable crop-growing potential. The range pentad for rainfall cessation for stations in the unimodal rainfall regime was 67–68, and the median was 68.

Onset, withdrawal and length of the October–December rainfall season

The results of the seasonal characteristics derived from mass curves for the selected stations where this season is dominant

TABLE 1: Onset and cessation of the March–May rainfall season at selected stations, the length of the potential crop-growing season and the planting window in Uganda.

Station type	Station	Range of planting window (pentad†)	Rainfall (pentad)				Length (days)		Peak rainfall pentads
			Onset		Cessation				
			Median	s.d.	Median	s.d.	Planting window	Growing season	
Bimodal rainfall regime	Katigondo	9–17	13	4	31	6	45	90	19–29
	Entebbe	11–17	14	3	31	3	35	90	19–28
	Mbarara	6–20	13	7	29	2	75	70	19–25
	Namulonge	10–16	13	3	32	4	35	100	19–25
	Kasese	9–17	13	4	30	4	45	70	19–26
	Kabarole	10–18	14	4	32	4	45	90	19–28
	Kabale	6–12	9	3	30	3	35	105	19–28
	Rukingiri	10–16	13	3	27	3	35	70	19–25
	Ivukula	10–20	15	5	32	3	55	95	19–25
Transition zone	Serere	12–20	16	4	33	6	45	85	19–29
Unimodal rainfall regime	Yumbe	16–22	19	3	68	3	30	245	42–59
	Nebbi	17–23	20	3	67	3	34	235	46–64

s.d., standard deviation.
†, In rainfall measurement, daily rainfall records are used to generate 5-day totals (pentads), giving a total of 73 pentads per year (i.e. the first 5 days of the year represent pentad 1 and the last 5 days represent pentad 73.

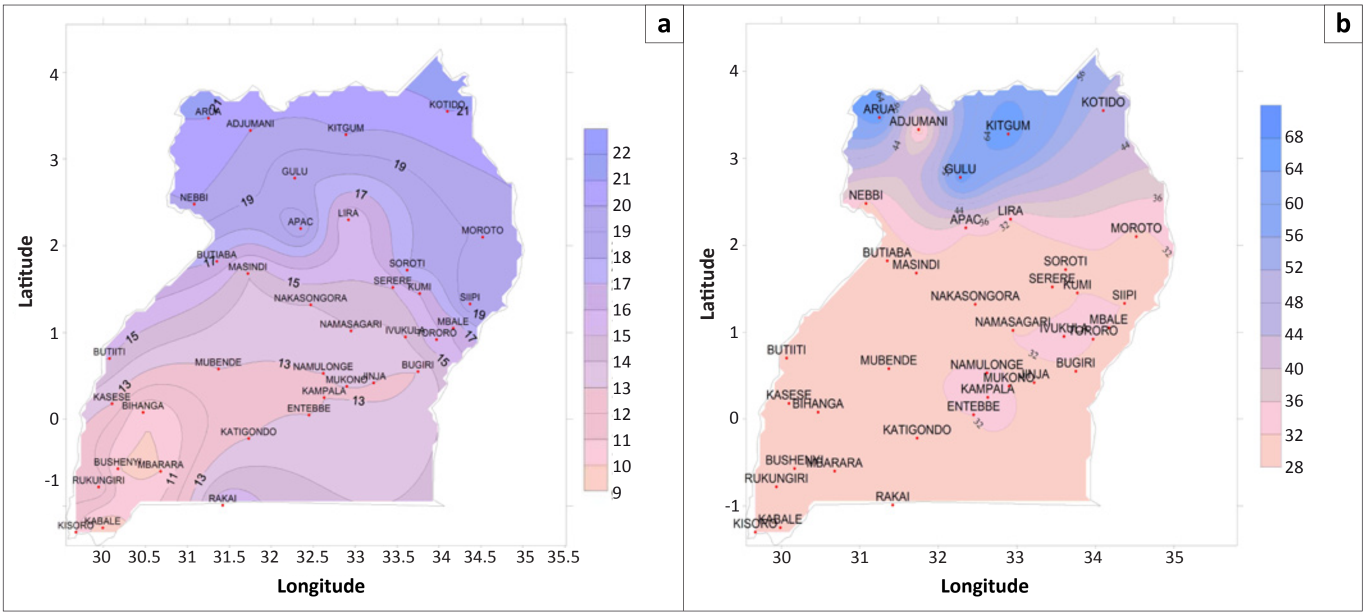


FIGURE 3: Spatial maps displaying (a) the onset (pentad) of rainfall and (b) the cessation (pentad) of rainfall for the March to May rainfall season in Uganda.

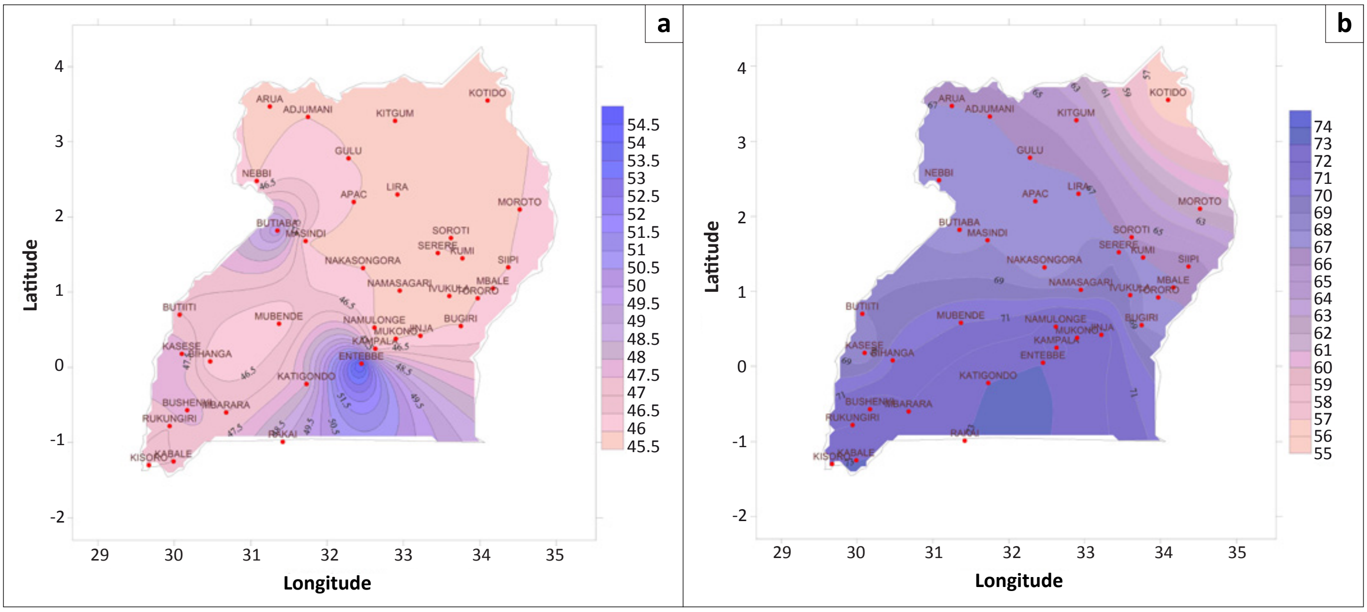


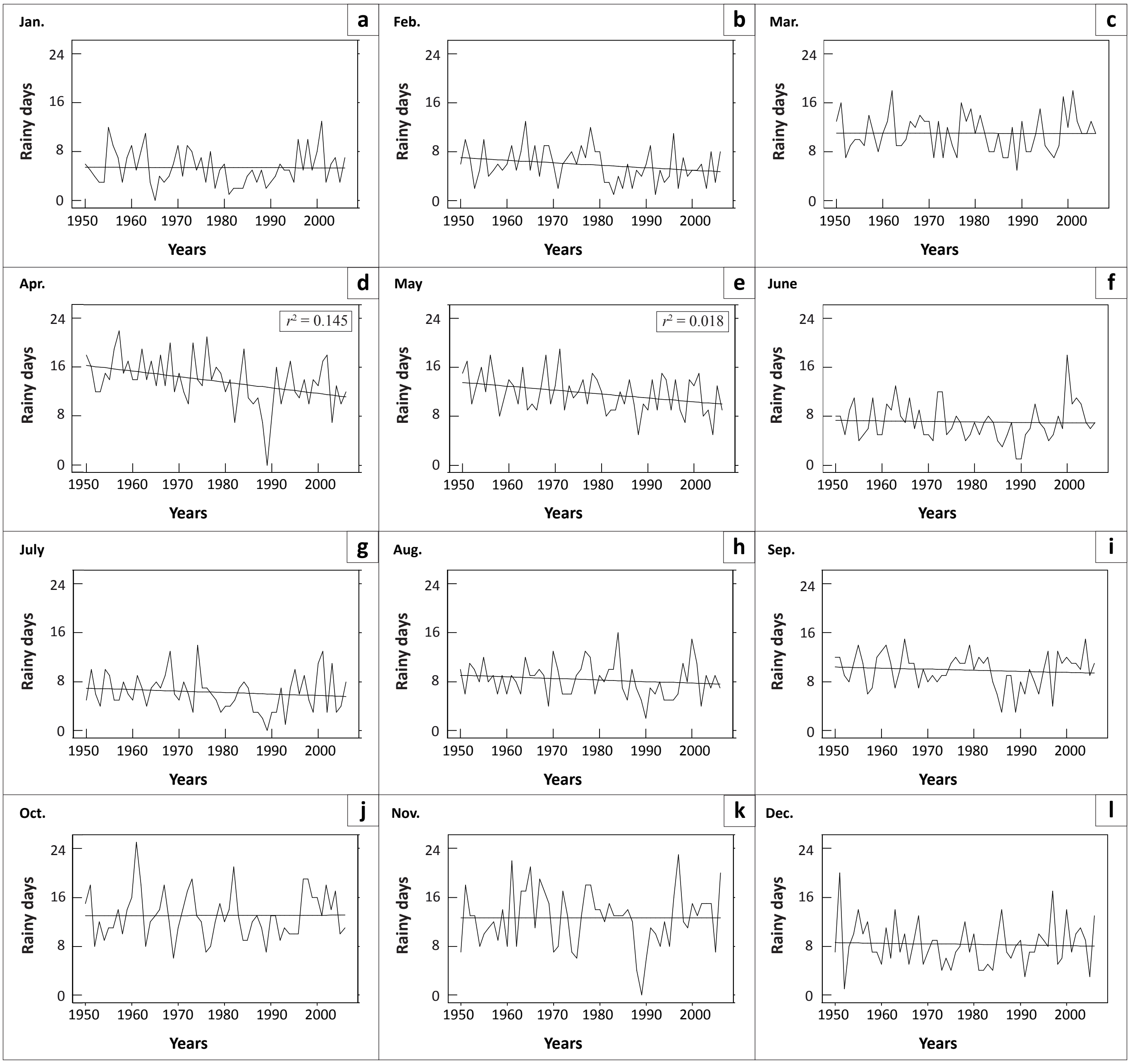
FIGURE 4: Spatial maps displaying (a) the onset (pentad) of rainfall and (b) the cessation (pentad) of rainfall for the October to December rainfall season in Uganda.

TABLE 2: Onset and cessation of the October–December rainfall season and the length of the potential crop-growing season at selected stations in Uganda.

Station	Range of planting window (pentad†)	Rainfall (pentad)				Length (days)		Peak rainfall pentads
		Onset		Cessation				
		Median	s.d.	Median	s.d.	Planting window	Growing season	
Soroti	42–50	46	4	66	5	44	100	50–70
Mbarara	44–50	47	3	72	1	34	125	56–66
Tororo	42–50	46	4	67	4	44	105	54–67
Entebbe	52–58	55	3	73	4	34	90	59–68
Masindi	41–51	46	5	68	4	54	110	58–68
Serere	43–49	46	3	69	4	34	115	50–64
Namulonge	42–50	46	4	73	4	44	135	59–68

s.d., standard deviation.
†, In rainfall measurement, daily rainfall records are used to generate 5-day totals (pentads), giving a total of 73 pentads per year (i.e. the first 5 days of the year represent pentad 1 and the last 5 days represent pentad 73.

are presented in Table 2. The onset and cessation for the October–December season seem to be less variable within stations and more uniformly distributed at most locations compared to the March–May season (Table 2 and Figure 4). The earliest and latest onsets of rainfall at each of the stations define the planting window for that location.



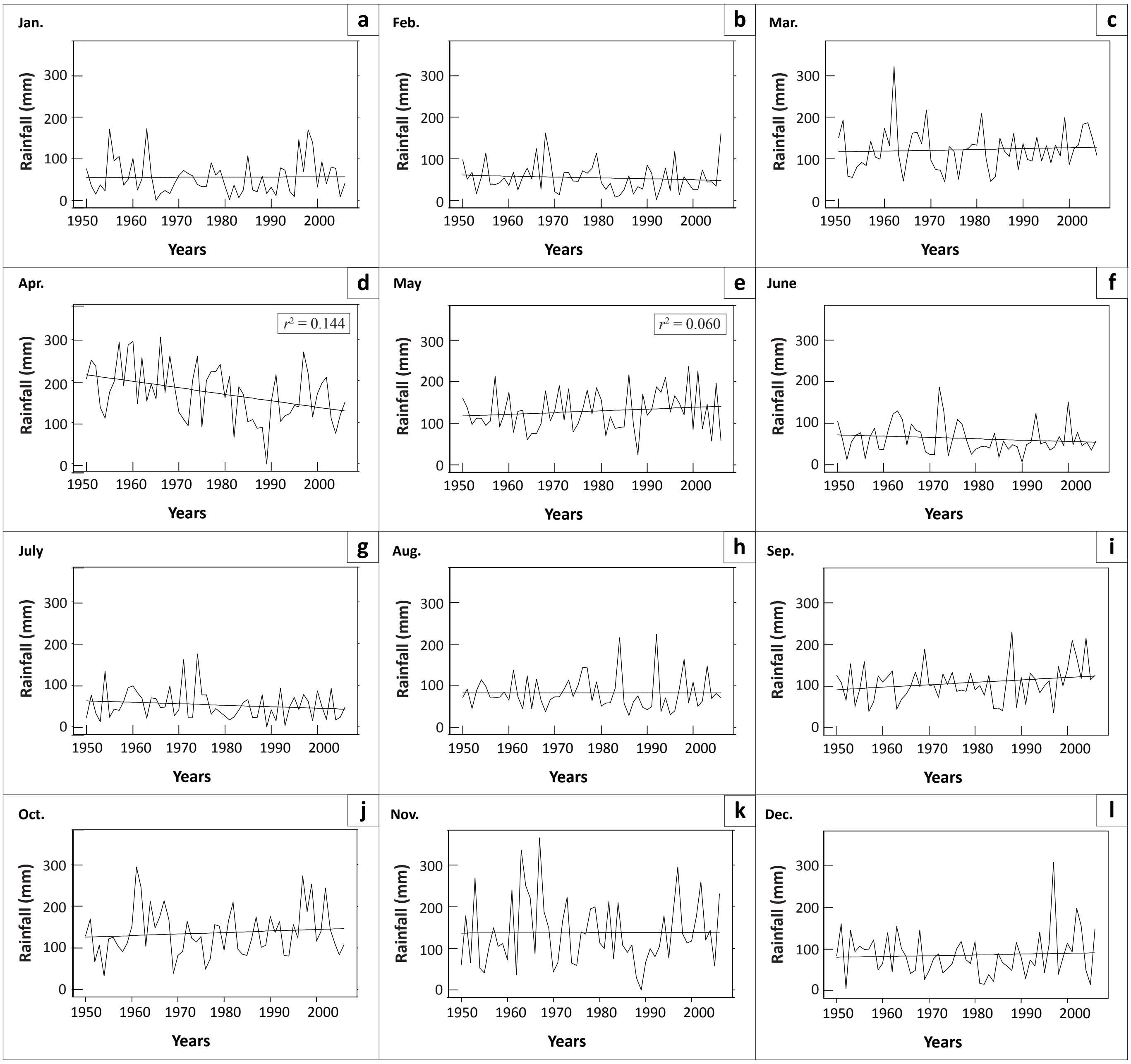
r^2-values indicate the linear correlation between the average number of rainy days for each month and the years (from 1950 up to 2000).

FIGURE 5: The number of rainy days at Namulonge Station in Uganda from 1950 to 2008.

The number of growing (or rainy) days and the early or late onset of rainfall do not necessarily indicate a favourable or unfavourable rainfall season. In some seasons, the rains started early and withdrew early, whilst in some cases they started late but also ended late, sometimes making the durations of the seasons average or longer. Such scenarios have made seasonal forecasting challenging, with some stakeholders suggesting that it is necessary to link forecasting with indigenous knowledge to make it more precise and relevant to the farmers.

Intraseasonal variations

In the bimodal rainfall regime represented by Namulonge Station in central Uganda, there seems to be a decreasing trend in the number of rainy days during the months of April and May and in the amount of rainfall during the month of April (Figures 5 and 6); unfortunately, April and May are the critical months of crop growth. The decrease in the amount of rainfall and the number of rainy days is manifested in unseasonable periods of no rain lasting from about 3 to 4 weeks interspersed within the rainy season. These unseasonable periods of no rain are becoming a common occurrence during the March–May season. This phenomenon renders crops grown in this season prone to climatic risks and therefore in need of adaptation measures. In their study, Jennings and Magrath[6] also noted that, within recognisable seasons, unusual and unseasonable events are occurring more frequently, for example, heavy rains in dry seasons, dry spells in rainy seasons and storms at unusual times. For Uganda in particular, they reported that farmers have noted increasingly unreliable rainfall during the March–May



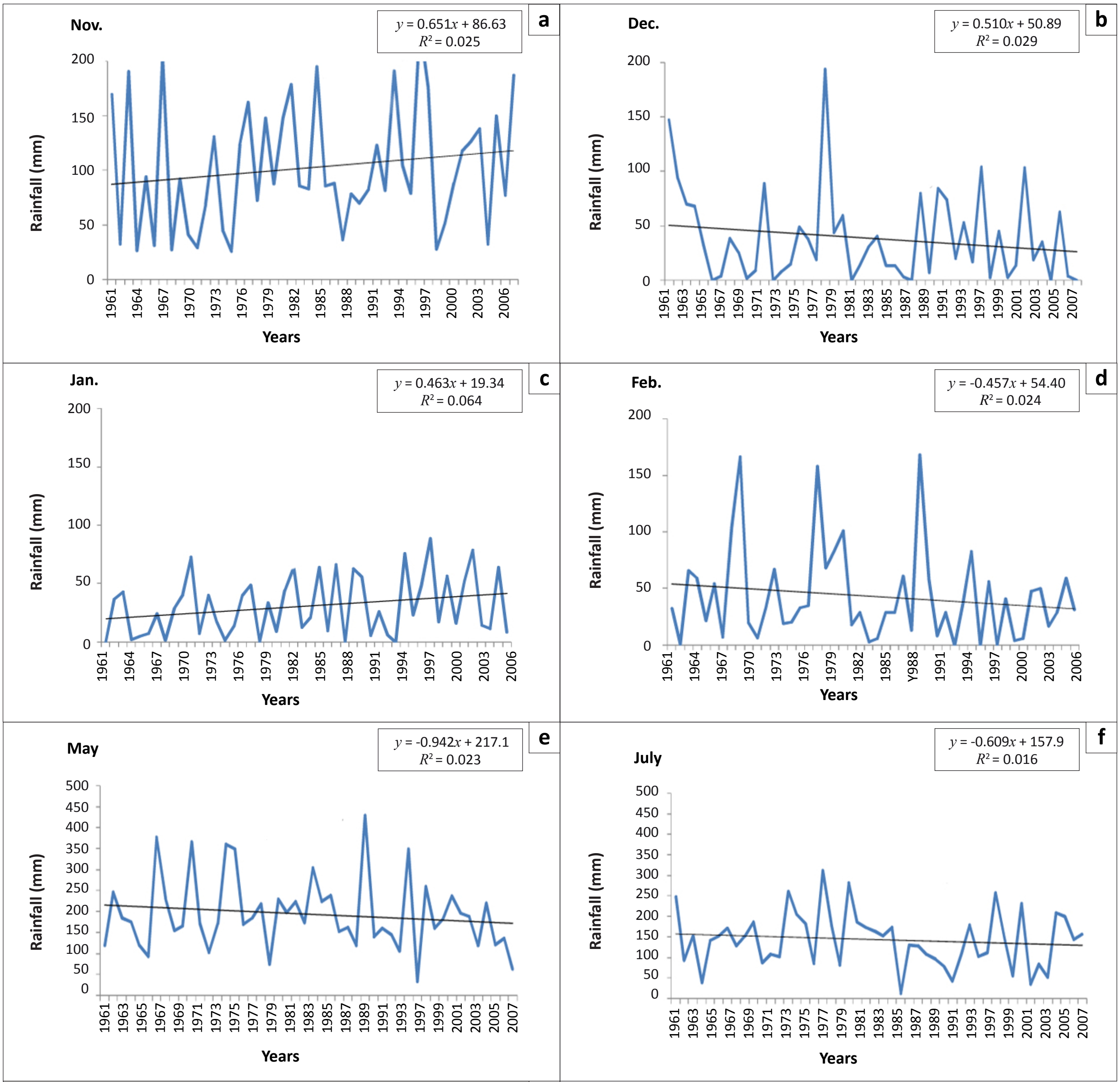
r^2-values indicate the linear correlation between the amount of rainfall for each month and the years (from 1950 up to 2000).

FIGURE 6: The amount of rainfall at Namulonge Station in Uganda from 1950 to 2008.

season, that is, the rain does not fall consistently throughout the season but rather comes in short, often localised, torrents interspersed with hot, dry spells.[6]

The relationship between the number of rainy days and the years, as well as between the amount of rainfall and the years, in the months of April and May were established through linear regression. Although the r^2-values are very small (Figures 5 and 6), the response of crop yield is non-linear and, in most cases, exponential. Therefore small spikes of moisture stress at the critical biological processes of yield formation can lead to a reduction in crop yields. The trends reflected on the graphs for April and May might be very significant in this regard, depicting a trend of concern during the first growing season in the areas represented by Namulonge Station.

In the transition zone represented by Soroti Station in eastern Uganda, the amount of rainfall during the months of November and January exhibited an increasing trend, whilst rainfall during the peak month of May showed a slight decreasing trend (Figure 7). North-eastern Uganda, represented by Kotido Station which is generally dry, experienced a unimodal rainfall regime commencing from April to November, with peak rainfall during April, May, July and August and a decrease during the month of June (Figure 8). This pattern has been consistent for years, as reported by Wilson[30] and Musiitwa and Komutunga[31], who observed that the rainfall in the subregion is characteristically episodic in occurrence, alternating with a prolonged severe dry season. They further noted that there is considerable variation from year to year in the total annual rainfall and



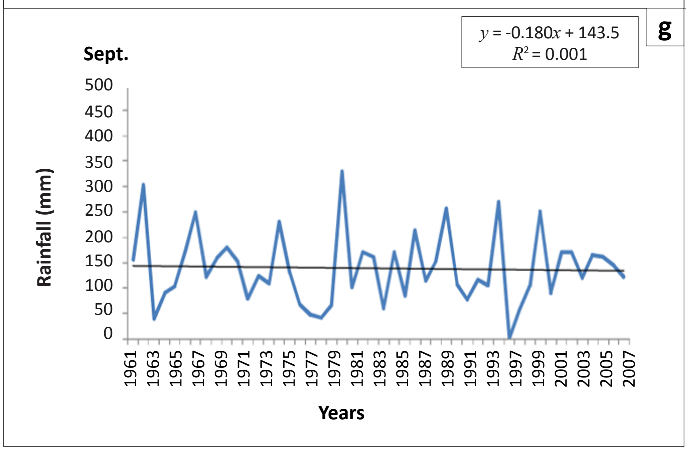


FIGURE 7: Monthly rainfall (mm) at Soroti Station in Uganda from 1950 to 2008.

moreover that the rainfall is not well distributed.[30,31] This observation is well illustrated in Figures 8 and 9: monthly and annual rainfall variability is high but without a consistent pattern. Further analysis shows that average monthly rainfall in June has been steadily increasing, whilst average monthly rainfall in September and October shows a declining trend (Figure 8).

Although the observed increase in the monthly rainfall in June is beneficial, as it comes in the middle of the season, the observed decrease in rainfall at the end of the season is detrimental, as it shortens the already short annual length of the potential crop-growing period of the region, posing challenges to pasture and crop-growing. Annual rainfall also

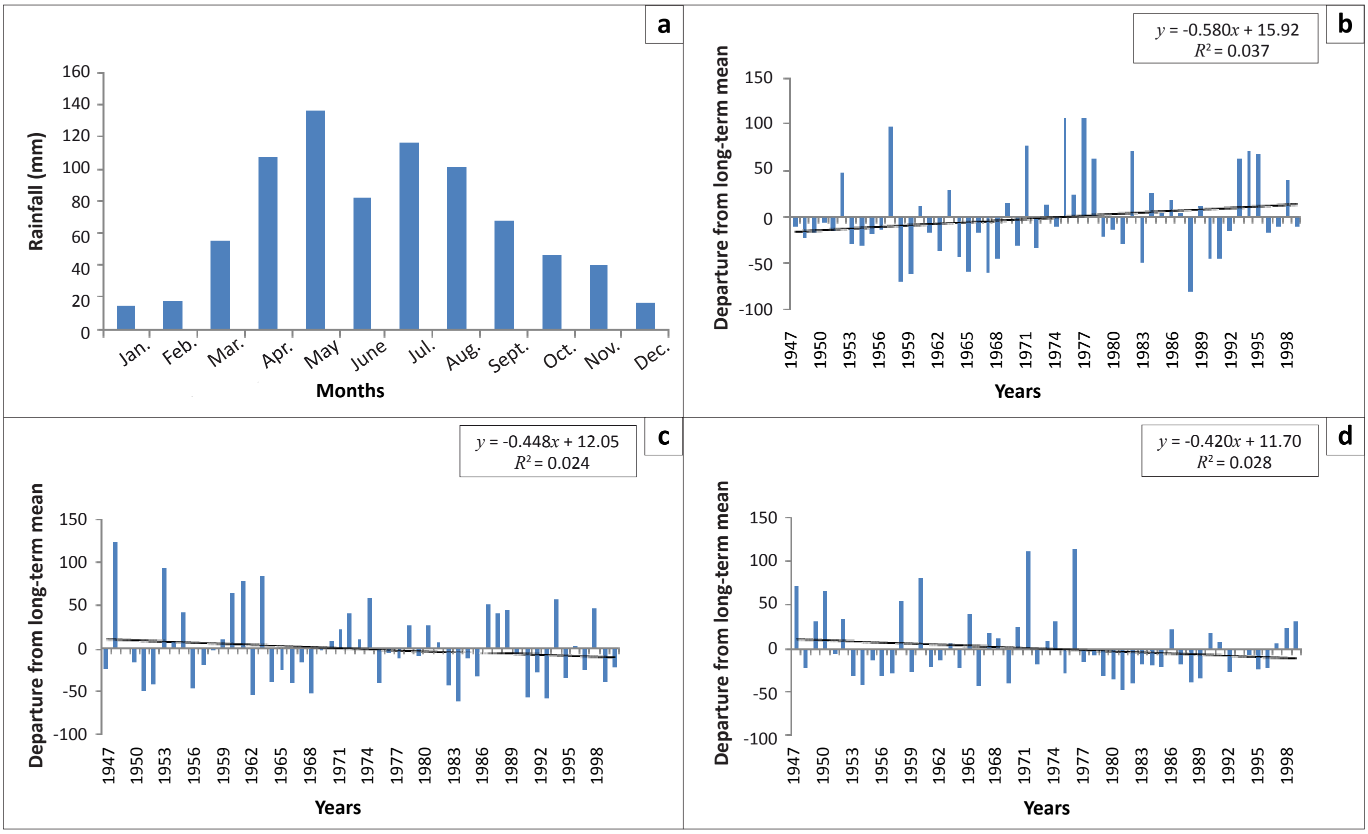


FIGURE 8: (a) Average monthly rainfall (mm) taken and the (b) June, (c) September and (d) October rainfall trends at Kotido Station in Uganda from 1947 to 2000.

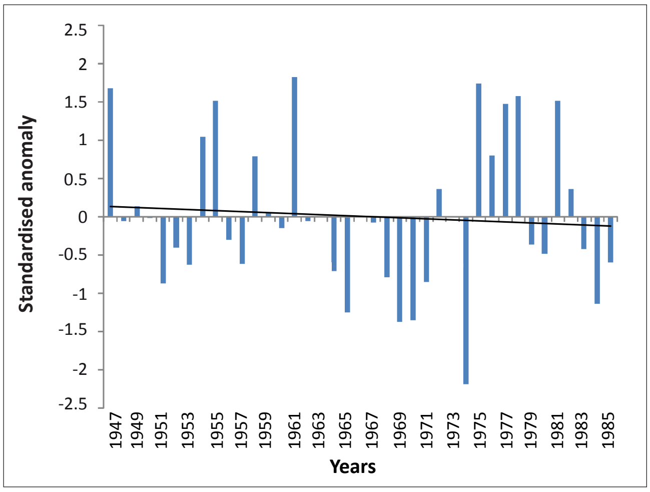


FIGURE 9: Annual rainfall variability at Kotido Station in north-eastern Uganda from 1947 to 1985.

shows a decreasing trend (Figure 9). Quantitatively, the rains received annually have decreased by about 15% – 20% since the 1960s. According to Anderson and Robinson[19], average annual rainfall has decreased by about 15%, but the deficit is further compounded by the way the rainfall arrives, because the intensity and duration between rainfall events has varied considerably. No longer can periods of reliable rainfall be assumed in one year out of every three.

The trends in rainfall across Uganda, described above, are a result of the complex interactions between the diverse topographical features of the country, the lakes and rivers and associated expanses of swamps, the wind systems over the country (including the trade winds), the intertropical convergence zone and the pressure systems. The rainfall regimes of Uganda have also been found to have teleconnections with sea surface temperatures in the Pacific, Indian and Atlantic Oceans, and the ENSO phenomenon.[26] Ogallo[26] further noted that the behaviour of these global systems resulting from global warming in turn affects the regional pressure systems, which in turn affect the local systems, resulting in the observed trends in rainfall over the country. The persistence of warm conditions over the Indian Ocean near Madagascar sucks in air from the East African region, depriving the region of moisture and creating dry conditions within the region. The western parts of the region, including Uganda, benefit from the moist air pulled in from the Congo forest and receive a rainfall boost. During the warm phase of the Pacific Ocean (El Niño) the region receives sufficient moisture, whilst in the cold phase (La Niña) the region receives little rainfall.

Temperature trends

Figure 10 shows the average daily maximum temperatures from 1950 to 2008. The temperature trend clearly shows that there has been an increase in temperature during this period. However, the lower limit of the range of daily maximum temperatures showed a faster rate of increase than the upper range. According to Mubiru et al.[3], the lower limit of the range of daily minimum temperatures also increased faster than the upper limit. The implication of these observations is that the day and night temperatures are becoming warmer.[3] As Thornton et al.[13] noted, the impacts of an increase in temperature, however small, will be far-reaching.

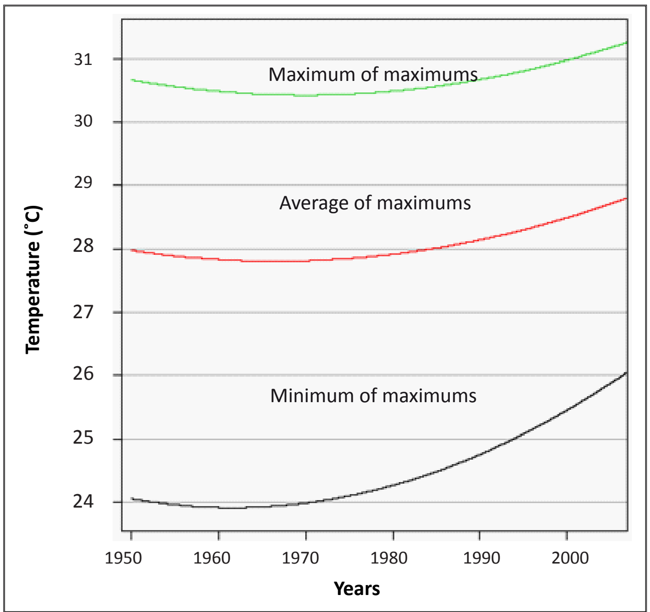


FIGURE 10: The trend of maximum temperatures in Uganda from 1950 to 2000.

Conclusions

We have generated information on seasonal rainfall characteristics relevant in exploiting the agricultural possibilities offered by climatic variability. Frequently, the onset of rains in the March–May season is delayed for as many as 30 days, with rains starting in mid-April instead of mid-March. However, the timing of rainfall cessation has more or less stayed the same, regardless of the time of onset of rainfall. Consequently, even when rains start late, withdrawal is timely, thus making the growing season shorter. In contrast, onset and cessation of the October–December season are less variable within stations and more uniformly distributed at most locations. At stations experiencing a unimodal rainfall regime, the average onset of rains is also quite stable.

On a monthly scale, there seems to be a decreasing trend in the number of rainy days during the critical months of crop growth in the March–May season, making crops grown in this season prone to climatic risks and therefore in need of adaptation measures. The average daily maximum and minimum temperature trends reveal an increase in temperature over the 50-year period. However, the lower limits of the ranges of the daily maximum and minimum temperatures are increasing faster than the upper limits. The implication of this finding is that the day and night temperatures are becoming warmer.

The seasonal information thus generated offers opportunities to exploit the seasonal distribution of rainfall to improve and stabilise crop yields through the incorporation of the seasonal characteristics of the onset, cessation and length of the crop-growing season. This information can also guide crop substitution and diversification.

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Competing interests

We declare that we have no financial or personal relationships which may have inappropriately influenced us in writing this article.

Authors' contributions

D.N.M. was the principal investigator and lead person in preparing the manuscript. E.K. performed the data analysis and constructed the graphs. A. Agona and T.N. made significant intellectual contributions for improving the technical content of the manuscript, whilst A. Apok played a key role in organising the data sets.

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